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ESTIMATING WATER CONTENT IN OILS: MOISTURE IN SOLUTION, EMULSIFIED WATER, AND FREE WATER.

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Abstract: This paper discusses the detrimental effects of moisture in lubricants, hydraulics, and transformer oils. It describes a means for automatic estimation of moisture content in lubricating oils, hydraulic fluids, and transformer oils. This is a field test method, used as an alternative when it is not convenient to measure water content by the Karl Fisher test or another analytical method. The total moisture content is found to be the sum of three separate measurements: moisture in solution, emulsified water, and free water. A single capacitive sensor is used to make all three measurements. Moisture in solution is instantaneously measured from a well mixed contaminated oil sample as compared to a similar measurement for a clean reference oil sample. Emulsified water is measured by determining the median-average rate of change in sensor output over time. Free water is measured by determining the accumulation of step changes in sensor output over time. The capacitive sensor is also used to identify the general oil type based upon the nominal dielectric value and upon the change in dielectric as a function of temperature change.

Key Words: Additive, dielectric, emulsified, moisture, oil, proactive, synthetic, water

Background: The measurement of moisture in lubricants, hydraulics, and transformer fluids using an automatic in-shop device is a valuable capability for industrial plant maintenance departments. Following is a list of some advantages for doing analysis on site:

- ownership and control;
- immediate results with immediate retest when needed;
- testing by people who know most about machinery;
- data is electronically stored with no transfer between lab and user; and
- test incoming fluids, with ability to fix problems, and verify correction.

The adage that "oil and water don't mix" is not entirely true. They do mix, to a greater or lesser extent, depending on oil base stock and additives. This paper addresses a method for evaluating water content, considering that water can either be in solution with the lubricant, emulsified with the lubricant, or carrying free water droplets in the lubricant. Before introducing the measurement methods, one should understand the answers to these questions.

- What are the functions of a lubricant? a hydraulic? a transformer oil?
- What are the effects of moisture in these fluids?
- In what forms does water exist in the oil?
- What are the effects of water on lubricant additives?

The answers to these important questions establishes the need to not only measure total water content, but to identify what amount is in solution, emulsion, or free state.

Functions of a Lubricant, Hydraulic, or Transformer: Lubricating oils serve multiple functions in mechanical systems. They reduce friction in each of the three lubrication regimes depending on application type: hydrodynamic, elastohydrodynamic (EHD), and boundary.

For applications with conformal bearings, such as Babbitt bearings, the lubricant transfers distributed loads, in the form of radial pressure, from shaft to sleeve. This regime is referred to as hydrodynamic lubrication and is similar to hydroplaning of an automobile on wet pavement

For highly loaded anti-friction bearings and gears, the viscosity of the lubricant must increase exponentially under the pressure due to lubricant being forced between the rolling element and the raceway. The lubricant viscosity increases until the oil has the bulk elastic modulus of a solid, and is able to transmit highly concentrated loads. Elastohydrodynamic lubrication practically eliminates metal to metal contact with extremely low frictional energy losses.

For traction type applications such as slides and wheels, the lubricant serves to reduce wear due to sliding contact and abrasion. In this case the physical loads are transmitted through-metal-to-metal contact. The traction or friction in this type of system can be very high, with coefficient of sliding friction as high as 1/3 of the normal force that presses the two components together. The friction, wear, and traction can be greatly reduced by lubricating the surface(s) so that only a limited amount of shear can be transmitted between components. This can be done with either solid lubricants (molybdenum disulfide or graphite) or with liquid lubricants including extreme pressure and anti-wear additives.

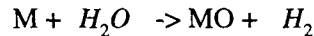
In addition to these requirements for transferring loads, reducing friction, and minimizing wear, lubricants fulfill several other functions critical to machine life. These include sealing surfaces from corrosion and other forms of chemical attack, transmitting hydraulic power, cleaning away contaminants and wear debris, cooling hot surfaces, and isolating (electrically) dissimilar metals from galvanic interaction. In the special case of transformer applications, oil provides cooling and electrical isolation (i.e., a low dielectric medium).

Effects of Water on Lubricants, Hydraulics, and Transformer Oils: Moisture is deleterious to most mechanical systems, hydraulic systems, and transformers. It causes problems by rendering the oil additives ineffective, by corroding metal surfaces, and by incapacitating elastohydrodynamic (EHD) lubrication.

Moisture chemically reacts with many oil additives thereby disabling their ability to provide antiwear, anti-oxidation, extreme pressure (EP), anti-foaming, and detergency functions. Moisture also consumes all or part of the dispersant and emulsifier additives intended to prevent contaminants from coalescing or agglomerating.

It is well known that moisture promotes corrosion of metal surfaces. Water is a reactive species at room temperature, especially towards metals. Typically metals under ambient conditions are

passivated and contain an oxide coating. However, metals that are under stress or wear may produce a "fresh" surface that is highly reactive. For example, a scratch or crack exposes metal resulting in the following reaction:

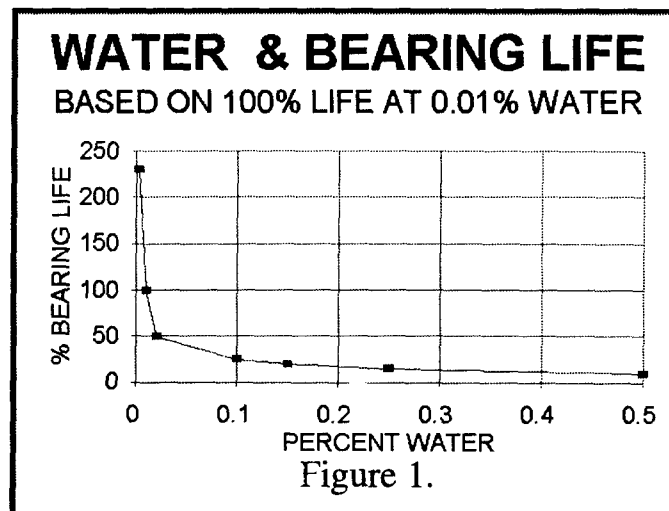


In this reaction the electron rich oxygen atom reacts with the electron deficient metal to form a new compound. The metal forms a new oxide coating and produces hydrogen gas. Depending on the metal (or alloy) present, the hydrogen may diffuse along grain boundaries, causing an effect known as hydrogen embrittlement, which accelerates wear rates.

The polar nature of the water molecule supports ionic mobility and encourages chemical attack to copper, lead, and other reactive metal surfaces, particularly in the presence of air and water. It also supports electrochemical interaction between galvanically dissimilar oil wetted metal parts leading to rapid corrosion.

As mentioned earlier, EHD lubrication depends on the unique pressure-viscosity property of mineral oils and synthetic lubricants. Free water droplets are unable to maintain physical separation between rolling elements or between gear teeth under these extremely high pressures. The resulting impacts can cause surface damage and shortened component life.

Water contamination of the lube or hydraulic oils shortens component and machine life. Timken Bearing Company report on the effect of water on bearing life as shown on the attached graph. Notice that reducing water contamination from 0.01% (100 ppm) to 0.0025% or (25 ppm) increases bearing life by a factor of 2.5 times!



The Form(s) of Water in Oil: There are three forms or states in which water is found when combined with oil. The water can be dissolved in the oil in the sense that it is hydrated, dissolved or reacted with additives that are mixed with the oil. In another state, oil can be dispersed or emulsified with the oil. Finally, it can be independently stratified or mixed as free water droplets which are separate from the oil. Each of these damages the oil and the mechanical system in a different way.

Moisture dissolved in the oil consumes performance enhancing additives and promotes corrosion. "Water's reaction with oxidation inhibitors produces acids and precipitates. These water-reaction

products increase wear and interferences. At high operating temperature (above 60 C), water reacts with and destroys zinc type antiwear additives. For example, zinc dithiophosphate (ZDTP) is a popular boundary lubricant added to hydraulic fluid to reduce wear in high pressure pumps, gears, and bearings. When this type additive is depleted by reacting with water, abrasive wear accelerates rapidly. The depletion shows up as premature component failure, resulting from metal fatigue and other wear mechanisms."¹ Other reactions produce acidic compounds which secondarily react with metal compounds of the machine the lubricant is intended to protect.

Water emulsified in oil consumes nearly all remaining additives, increases corrosion, and changes fluid viscosity (normally increasing it). Systems designed to operate with water present must either *emulsify* or *demulsify* the water to extend life of mechanical parts. This is discussed in more detail in later sections of this paper. Automotive applications must emulsify the water until it can be driven off by heat. Steam turbines typically demulsify water, dropping it out in the oil compartment (sump) where it can be bled off. In either of these cases, water left in the system can lead to corrosion and even microbial growth. Under certain conditions, microbial bacteria can live and reproduce very rapidly when sufficient water is present in oil. These living organisms can ruin the oil system, clogging filters, changing water emulsion characteristics, increasing corrosion rates and producing acidic waste products.²

Free water droplets, which occur after the oil has been fully saturated, are desirable in some lubricating systems (those designed to demulsify water) and very detrimental in others. This is explained in the following paragraphs.

The Effects of Moisture on Oil Additives: In mineral oils and polyalphaolephin (PAO) synthetic hydrocarbon oils, additives are required for any significant amount of water either to be dissolved in oil or to be emulsified with oil. The polar nature of the water molecule and the non-polar nature of the hydrocarbon mineral oil make them immiscible. Pure mineral oils and transformer oils are saturated with as little as 5 ppm water, and turbine oils saturate with as little as 200 ppm water. Above saturation level, water coalesces into free water droplets eventually settling to the bottom of the oil compartment.

This is a very desirable characteristic for most steam turbines³ and paper machines⁴. In these applications, water contamination is common. So to avoid the consequences of moisture retention in these machines, oils are designed to demulsify, or drop water out, in the oil

¹"Walking the Fluid Cleanliness Tightrope, Part 2," by Al Zingaro, *Hydraulics and Pneumatics*, December, 1994, pg. 26.

²"Microbial Problems in Metal Working Fluids," by Frederick Passman, Angus Chemical Company, Northbrook, IL, *Starting from Scratch: Tribology Basics*, STLE Publication.

³"Delivery Control of Lubricating Oil," K-Standard K-1171-7, dated 94-07, ABB Stal.

⁴"New Direction for Paper Machine Lubricants, Ashless vs. Ash Type Formulas," by Dr Louis R. Kray, et. al., Chevron Research and Technology Company, Richmond California, *Lubrication Engineering*, October, 1995, pg. 834-838.

compartment before returning to the machine. Then periodically, water is bled off from the bottom of the oil compartment (e.g., sump). Demulsibility of oil is good if water separates quickly at operating temperatures. It is bad if it separates slowly.

These oils which demulsify water are normally pure mineral oils or PAOs with very little additive. Mr. N. G. Nilsson of ABB Stal points out that one liter of automotive lubricant has enough additive to destroy the demulsification characteristics of 6000 liters of turbine oil, if one were to accidentally mix the two types. In fact, when additive concentrations > 1.0 ppm for Ca, Mg, or Ba are found, then emulsion characteristics of the oil must be validated by ASTM 1401 emulsion test to demonstrate clear separation of water from oil within 15 minutes at 54 C. This ensures that water picked up in the turbine will be dropped out in the oil compartment before returning to lubricate the machine again.

TABLE I

ADDITIVE ELEMENTS		RANGES	ADDITIVE ELEMENTS		RANGES
AUTOMOTIVE			E P ADDITIVE GEAR OIL		
MAGNESIUM		50-400 PPM	SODIUM		75-500 PPM
SODIUM		0-200 PPM	BORON		998 PPM
BARIUM		0-150 PPM	PHOSPHORUS		175-425 PPM
PHOSPHOROUS		700-1300 PPM	CALCIUM		10-150 PPM
CALCIUM		400-2000 PPM	ZINC		300-550 PPM
ZINC		800-1400 PPM	TOTAL		≈ 1500 PPM
TOTAL		≈ 4000 PPM	HYDRAULIC OILS		
INDUSTRIAL GEAR OIL			BARIUM		0-200 PPM
BARIUM		0-25 PPM	PHOSPHORUS		225-325 PPM
PHOSPHOROUS		300-750 PPM	CALCIUM		25-150 PPM
CALCIUM		5-50 PPM	ZINC		350-500 PPM
ZINC		500-1000 PPM	TOTAL		≈ 1000 PPM
TOTAL		≈ 1500 PPM	COMPRESSOR OILS		
			BARIUM		0-200 PPM
			PHOSPHORUS		0-35 PPM
			CALCIUM		0-35 PPM
			ZINC		0-50 PPM
			TOTAL		≈ 200 PPM

Engine oils and many other lubricants will tend to *emulsify* rather than *demulsify* water. The additives in these serve to disperse water and prevent it from coalescing into free water droplets. Additives modify the solubility and emulsion character of mineral oils. Transformer oils saturate with 3 to 10 ppm water. Oil-base hydraulic fluids are typically saturated with 100 ppm (0.01%) to 1000 ppm (0.1%) water⁵. Industrial lubricants are typically saturated with 600 ppm (0.06%) to 5000 ppm (0.5%) water. Automotive lubricants are typically saturated with 1% to 5% water. Stern tube oils (those used to lubricate the aft bearing on a ship propulsion shaft) have been tested with 16% water with no evidence of saturation. Each of these lubricants has increasing amounts of additive, particularly increasing amounts of total dispersant + detergent + anti-oxidant + anti-wear + extreme pressure.

⁵"Walking the fluid Cleanliness Tightrope, Part 2," by Al Zingaro, *Hydraulics and Pneumatics*, December, 1994, pg. 25-26.

One can estimate the percentage of additive in a lubricant from the total ppm of additive elements including Zn, Ca, Mg, P, K, Ba, and sometimes Na. Table I displays typical ranges for elemental compositions of additive for various lubricant types.⁶

Traditional Water Measurement Methods used by Oil Labs: Several different methods are used in oil laboratories to measure moisture content of lubricants, hydraulics, and transformer oils. Three of the more common methods are Fourier Transform Infrared (FTIR), the "crackle" procedure, and Karl Fisher procedure.

The FTIR is a form of infrared absorption spectroscopy used to identify and quantify organic functional groups within the oil molecular structure. Water exhibits an absorption peak at 2.9 micron and 9.6 micron wavelengths. Results are typically reported with an index value commonly called, "*absorption units*" or *AU*⁷. Some industrial fluid analysis laboratories use the FTIR method to flag samples containing water for subsequent testing using the Karl Fisher method.

Crackle is a qualitative test in which a few drops of oil are placed on a hot surface (about 130 C). If water is present, it quickly boils and sputters, giving audible indication. Although this is a very widely used test, "it is extremely subjective, and does not indicate the actual level of water present."⁸ Since the crackling sound results when free water boils, it is not a good method for measuring water in solution and has limitations with respect to emulsified water measurement.

Water content by the Karl Fisher method (ASTM D1744) is a very accurate test, particularly for small amounts of water (<1000 ppm or 0.1%) although it can be used for greater levels of contamination as well. This procedure involves wet chemistry titration to an end point, reacting an oil sample with the Karl Fisher reagent. It is normally done in a ventilated laboratory.

Time-base Capacitance Measurement Apparatus: A time-base capacitance measurement apparatus⁹ was evaluated with respect to water contamination measurement capabilities. This device is intended to be used in plant maintenance departments for the purpose of immediate testing of used lubricants. In addition to measuring moisture, the device also reports on wear condition and lube quality which was first reported in 1992.¹⁰

⁶"Oil Analysis and Wear Particle Analysis", by E. Zigler, DuPont Accession Report 17677, Dated April 1991, presented to the *1991 PPM Users Seminar*, May 14-16, 1991.

⁷"Tech Traks" by Lubricon, Lubricant Consultants, Inc., Box 51506, Indianapolis, IN.

⁸"Oil Analysis, Part 2 - Determining What Tests to Run," reprinted from *Fluid and Lubricant Ideas*, Amsoil Corporation, document G-286, pg. 6.

⁹The apparatus used is the OilView Analyzer available from Computational Systems Incorporated, Knoxville, Tennessee 37932, (423) 675-2110.

¹⁰"Portable Oil Analyzer for Predictive and Proactive Maintenance," by J. Kirkpatrick, Computational Systems, Incorporated, *Annual Meeting of the Vibration Institute*, 1992.

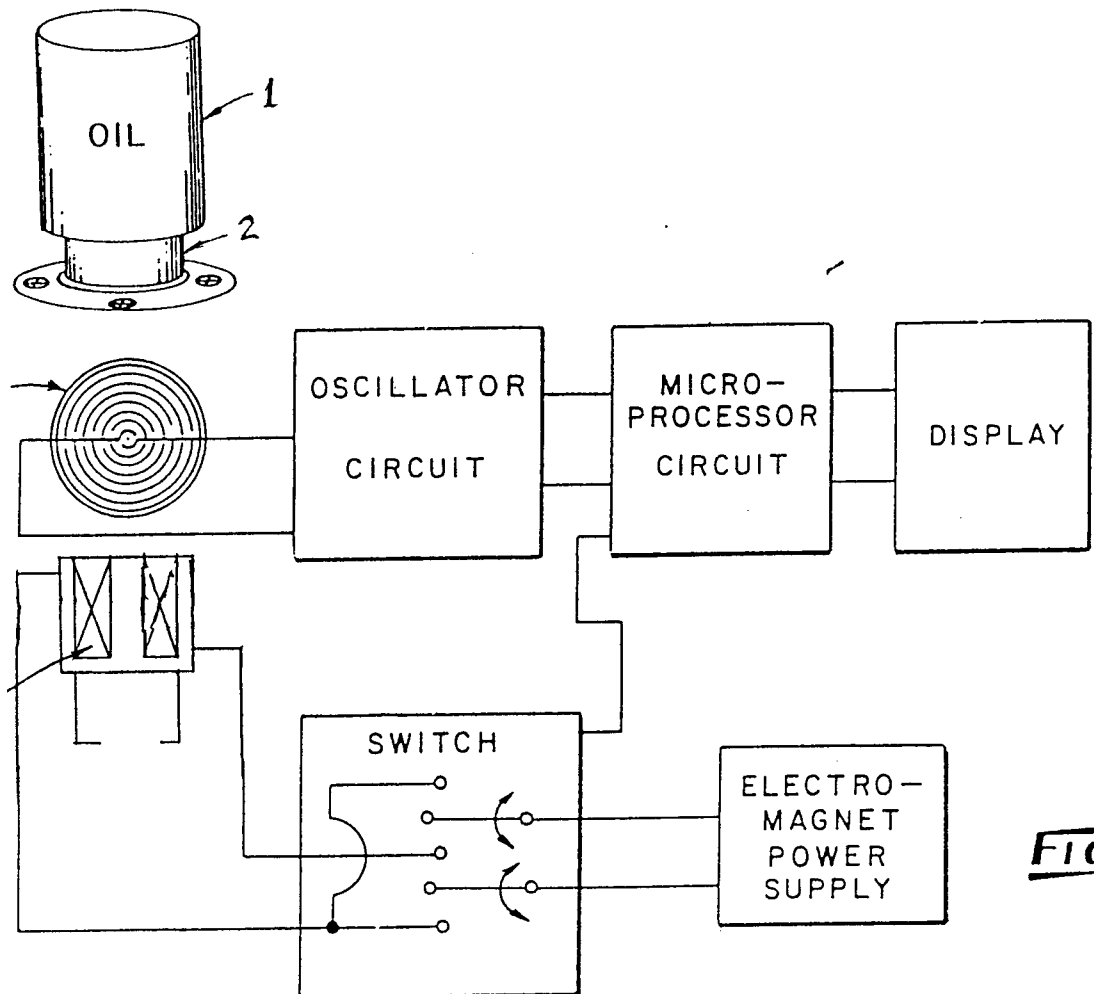


Fig 2

The apparatus which is used to estimate water in the oil employs a time-based measurement from a capacitive sensor at the bottom of an oil sample. See Figure 2. A sample of oil is poured into a wide mouth (item 1 on Figure 2) sample bottle (item 2). The sample is attached and sealed over a capacitive sensor (item 3) and then is shaken until the sample is homogenous. Then the sample is allowed to settle for a period of time, typically 500 seconds, while the microprocessor controls an oscillator circuit which tracks the natural frequency of the capacitive sensor.

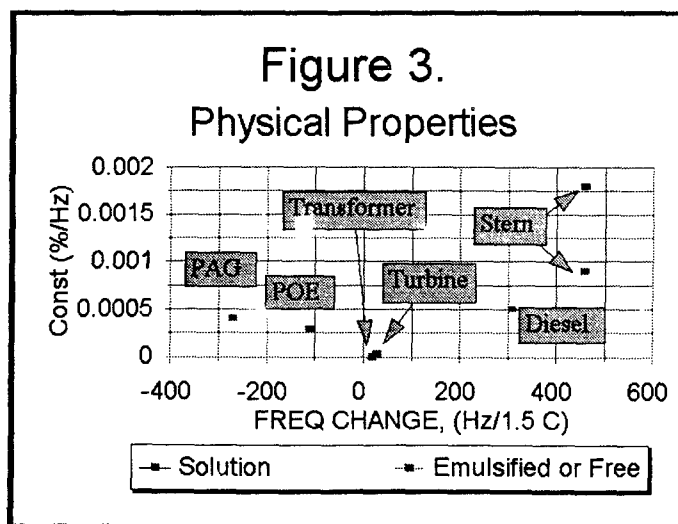
The capacitive sensor (item 3) consists of two non-intersecting conductor traces. The substrate beneath the traces is fiberglass or another good dielectric material. The capacitance of the sensor (item 3) is a relative measure of the dielectric constant for the oil covering the space between the traces. A low relative dielectric constant for the oil produces a low capacitance for the sensor, which in turn causes a high natural frequency for the oscillator circuit. This is the case when new, uncontaminated oil is placed on the sensor - the frequency is relatively high because the oil is a very good insulator (e.g., it has a very low dielectric constant, <2.5). On the other hand, when water is present on the sensor, the capacitance increases and the frequency drops.

The electromagnet (item 4 in Figure 1), has a primary function assisting in the measurement of ferrous wear debris. This electromagnet also plays an important role with respect to water measurement -- it heats the reference oil approximately 1.5 C during the 500 second test time. This slight heating triggers a change in dielectric value as a function of temperature which can be used to identify the type of class of lubricant.

The abscissa (X-axis) on Figure 3 shows how the change in sensor frequency, labeled "frequency change," due to electromagnet heating (approximately 1.5 C) varies with oil type for mineral and synthetic oils. This fingerprint response is used to characterize reference oil samples with respect to general type or class of lubricant (e.g., PAG, POE, transformer, turbine/hydraulic, diesel engine, or stern oil).

Each class of lubricant has a different affinity for water due to its base oil and additive composition.

The ordinate (Y-axis) on Figure 3 shows an empirically derived constants for water affinity of each oil type. This material constants are displayed with units of "Percent water per Hz" of sensor output. These constants, when multiplied by the measured frequency output, yield the water content in each of three physical states: solution, emulsified, and free.



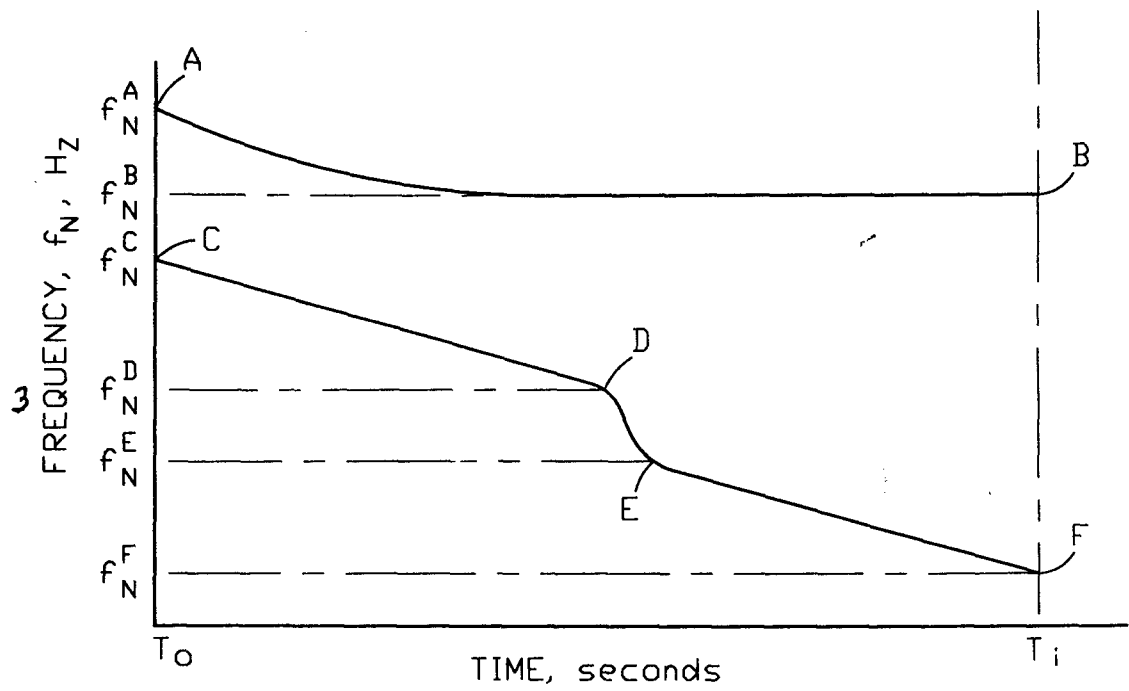


Fig. 4

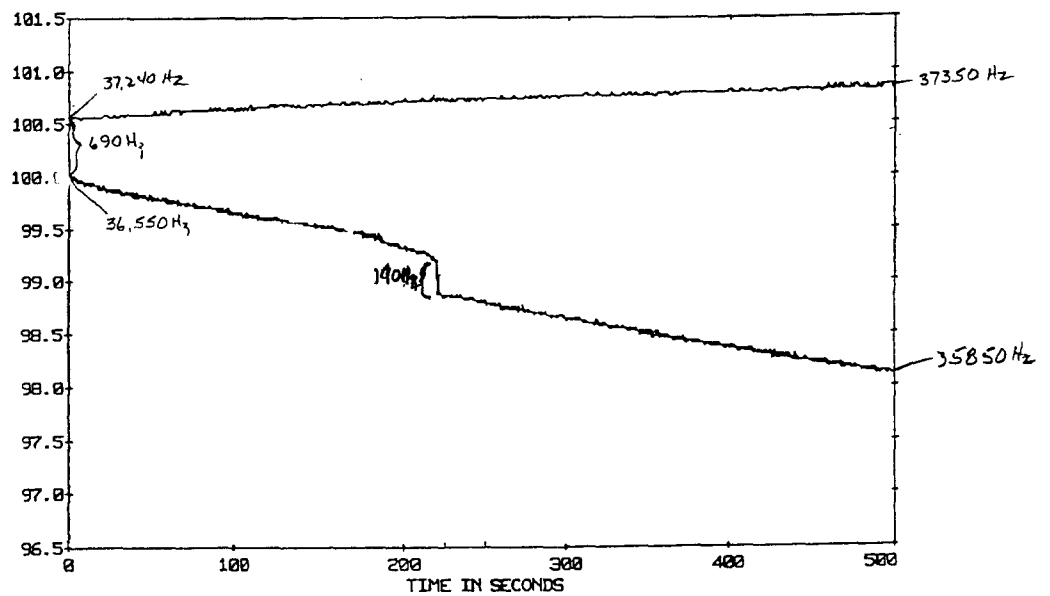


Fig. 5

TABLE II

TEST	LUBRICANT	% H ₂ O			NATURAL FREQ.			Δf, Hz			Δf, Hz			RATE			ppm Additive	H ₂ O, %			H ₂ O, %			Error	
		Actual	Calc	B	Start	End	F	G	H	I	J	Solution	Emul	Free	K	L		M	N	Free	Sum	Diff	P		
1	POE (1)	0	0		37240	37350	0	0	-110	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵		0	0	0	0	0	0	0		
2		0.04	0		37220	37240	0	-20	-20	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵		0.00572	0.02574	0	0.03146	-0.00854				
3		0.08	0		37200	37170	0	-40	30	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵		0.01144	0.04004	0	0.05148	-0.02852				
4		0.16	0.1		36880	36880	0	-230	130	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵		0.06578	0.06864	0	0.13442	-0.02558				
5		0.32	0.3		36550	35850	140	-690	700	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵		0.19734	0.19162	0.04004	0.429	0.109				
6		0.64	0.6		36110	34990	0	-1130	1120	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵		0.32318	0.35178	0	0.67496	0.03496				
7		1.28	1.2		35930	33130	0	-1310	2800	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵	28.6 x 10 ⁻⁵		0.37466	0.83226	0	1.20692	-0.07308				
8	PAG (2)	0	0		29920	30190	0	0	-270	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵		0	0	0	0	0	0			
9		0.04	0		29800	30070	0	-120	-270	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵		0.048	0	0	0.048	0.008				
10		0.08	0		29710	29990	0	-210	-280	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵		0.084	-0.004	0	0.08	0				
11		0.16	0.1		29540	29810	0	-380	-270	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵		0.152	0	0	0.152	-0.008				
12		0.32	0.2		29160	29410	0	-760	-250	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵		0.304	0.008	0	0.312	-0.008				
13		0.64	0.4		28520	28780	0	-1400	-260	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵		0.56	0.004	0	0.564	-0.076				
14		1.28	0.8		27070	27180	0	-2850	-110	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵	40.0 x 10 ⁻⁵		1.14	0.064	0	1.204	-0.076				
15	DIESEL	0	0		60960	60650	0	0	310	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵		4000	0	0	0	0	0			
16		0.1	0.05		60680	60300	0	-280	380	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵		4000	0.14	0.035	0	0.175	0.075			
17		0.5	0.41		60600	59530	0	-360	1070	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵		4000	0.18	0.38	0	0.56	0.06			
18		0.75	0.79		60050	58480	0	-910	1570	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵		4000	0.455	0.63	0	1.085	0.335			
19		1	0.89		60430	58690	0	-530	1740	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵	50.0 x 10 ⁻⁵		4000	0.265	0.715	0	0.98	-0.02			
20	TURBINE	0	0		59530	59500	0	0	30	2.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵		1	30	0	0	0	0			
21		0.03	0.01		59240	58700	0	-290	540	2.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵		1000	0.0058	0.0204	0	0.0262	-0.0038			
22		0.13	0.13		59520	56110	0	-10	3410	2.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵	4.0 x 10 ⁻⁵		1000	0.0002	0.1352	0	0.1354	0.0054			
24	TRANSF	0	0		59720	59700	0	0	20	12.6 x 10 ⁻⁷	13.0 x 10 ⁻⁷	13.0 x 10 ⁻⁷	13.0 x 10 ⁻⁷	13.0 x 10 ⁻⁷	13.0 x 10 ⁻⁷		200	0	0	0	0	0			
25		0.005	0.1		59690	55740	0	-30	3950	12.6 x 10 ⁻⁷	13.0 x 10 ⁻⁷	13.0 x 10 ⁻⁷	13.0 x 10 ⁻⁷	13.0 x 10 ⁻⁷	13.0 x 10 ⁻⁷		200	3.8 x 10 ⁻⁵	0.004952	0	0.00499	-1.0 x 10 ⁻⁵			
26	STERN	0	0		50290	49830	0	0	460	18.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴		6000	0	0	0	0	0			
27		2.3	3		49090	47110	0	-1200	1980	18.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴		6000	2.16	1.368	0	3.528	1.228			
28		5.7	5.3		47970	45510	0	-2320	2460	18.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴		6000	4.176	1.8	0	5.976	0.276			
29		11	9.3		45400	42650	0	-4890	2750	18.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴		6000	8.802	2.061	0	10.863	0.137			
30		16	12.7		43180	39960	0	-7110	3220	18.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴	9.0 x 10 ⁻⁴		6000	12.798	2.484	0	15.282	-0.718			

Figures 4 and 5 show the sensor frequency vs. time plot for a clean reference oil sample (AB) and a contaminated used oil sample (CDEF). Water content is computed from the data reported in these curves in the following manner. Actual data which have been collected on a variety of oil types are reported in Table II. Values for starting frequencies, "A" and "C" are given in column D. Values for ending frequencies, "B" and "F" are given in column E. Step changes, "D-E", are given in column F. The example shown in Figures 4 and 5 is taken from test number 5 with POE (column A) having actual water content of 0.32% (column B). Actual water content was determined by using a precision micropipet to measure water added to reference oils for all data reported herein.

Measuring Moisture in Solution: Three elements are needed to compute moisture content in solution: (1) the identity of the lubricant type, (2) the water affinity constant for this type of lubricant, and (3) difference between the starting frequency of the new vs. used oil samples.

The identity of the lubricant type can be input by the individual doing the test, or it can be automatically determined using frequency difference, A-C, in conjunction with Figure 3. The water affinity constant for this lubricant type is then obtained from column "T" in table II (also graphically represented in Figure 3). Moisture in solution is then computed from the following:

$$\text{Moisture in Solution} = (A-C) \times (\text{Solution Constant})$$

Measuring Emulsified Water Content: Three elements are needed to compute emulsified water content: (1) the identity of the lubricant type, (2) the water affinity constant for this type of lubricant, and (3) the median-average slope for the curve CDEF.

The identity of the lubricant type can be input by the individual doing the test, or it can be automatically determined using frequency difference, A-C, in conjunction with Figure 3. The emulsified water affinity constant for this lubricant type is then obtained column "J" in Table II (also graphically represented in Figure 3).

Emulsified water content is then computed from the following:

$$\text{Emulsified water content} = \text{Median Average Slope } \overline{[CDEF]} \times (\text{Emulsibility Constant})$$

Measuring Free Water Content: Three elements are needed to compute free water content: (1) the identity of the lubricant type, (2) the water affinity constant for this type of lubricant, and (3) cumulative step changes in the slope of the sensor output vs. time plot.

The identity of the lubricant type can be input by the individual doing the test, or it can be automatically determined using frequency difference, A-C, in conjunction with Figure 3. The free water affinity constant for this lubricant type is then obtained column "J" in Table II (also graphically represented in Figure 3). Moisture in solution is then computed from the following:

$$\text{Free water content} = (D-E) \times (\text{Free Water Constant})$$

Figure 6

STERN OIL - UP TO 16 % WATER

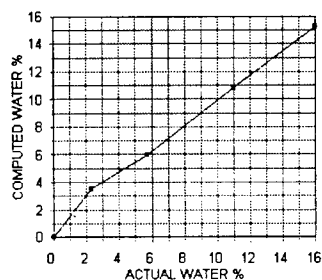


Figure 7

DIESEL OIL - UP TO 1% WATER

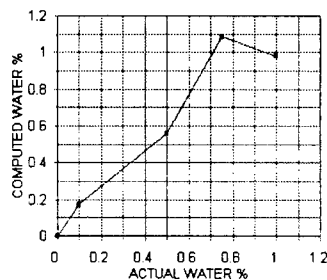


Figure 8

TURBINE OIL - UP TO 0.13% WATER

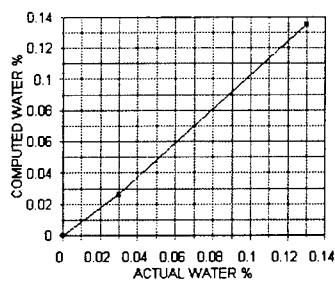


Figure 9

POE OIL - UP TO 1.28% WATER

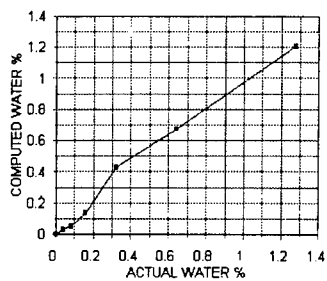


Figure 10

PAG OIL - UP TO 1.28% WATER

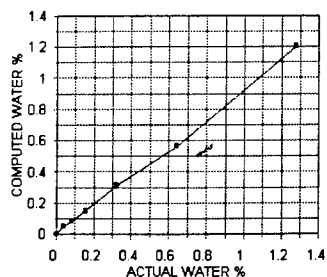
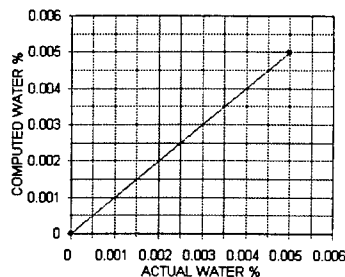


Figure 11

TRANSFORMER PAG OIL - UP TO 5 PPM WATER



Total Water Content: The total water content is simply the sum of the three parts: solution, emulsion, and free. Figures 6 to 11 show data measured on a variety of different oil types, comparing actual water content to calculated total water content. All of these data are reported in Table II.

Removal of water: There are a number of different actions one might take after detecting water in lubricated machinery:

- Do nothing
- Operate at high temperature
- Change the oil
- Centrifugal separation
- Vacuum dehydration
- Coalescing filtration.
- Bleed from bottom of oil compartment

There are advantages and disadvantages, costs and benefits to each of these approaches. The selection of the best approach depends on the application and form(s) of water to be removed.

The "do nothing" alternative may be the best short term action, at least until repair intended to prevent ingress of coolant or water can be accomplished. All too often, the first action after undesirable water is detected is to drain and replace the oil. This action can be a waste if the cause of water contamination is not identified and corrected first.

Water is naturally driven off by heat. This method of water removal is only practical for high temperature operating systems with vented oil compartments. For example moisture, which is a product of combustion and condensation, is driven off when the engine operates at 100 C for a sustained period. The low vapor pressure of moisture in solution and emulsified water makes this makes this impractical for most industrial applications which operate below 50 C.

Changing the oil may be the lowest cost method to remove water, *after* the source of contamination has been eliminated. Naturally, this removes all three forms of water.

Centrifugal separation is an effective means for maintaining the cleanliness of the lubricant with respect to free water and most of the emulsified water. Centrifugal separators cannot remove moisture from solution which is chemically bound to additives or synthetic base stock.

Coalescing filters use a gel with high affinity to absorb water from the oil. These filters have limited water capacity and can be relatively expensive. They are best used to maintain low water contamination in systems which are not prone to ingress of very much water.

Finally, many lube systems are designed to demulsify free water in the oil compartment so that it can be bled off periodically. This approach works very well unless oil additives are used which support emulsified water. These oil compartments tend to be relatively large. The supply side of the oil compartment should be tested to verify absence of free and emulsified water going back into the lubricated machinery.

Conclusion: Moisture contamination of lubricants, hydraulics, and transformer oils lead to a variety of problems, all of which shorten machine life through corrosion, electrochemical interaction, and greatly accelerated wear rates. Water combines with the oils in the form of a solution, an emulsion, or a mixture of free water in oil.

The time-based capacitance apparatus was demonstrated to have the ability to measure the quantity of water in each of these forms. Moisture in solution is quantified by comparing the dielectric constant of a vigorously shaken contaminated oil sample with a clean oil sample. Emulsified water is quantified by determining the settling rate of moisture laden oil within this sample. Free water is quantified by monitoring the discrete step-changes in time as drops fall to the sensor surface.

By monitoring these three forms of water contamination in oil, industrial maintenance departments are able to take proactive measures to preclude the damaging effects water has on machinery.